Fault Ride-through Enhancement of Wind Energy Conversion System Adopting a Mechanical Controller

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***Abstract*—In recent years, wind has become the fastest growing energy source in the electrical power generation. A large amount of electric power is generated from wind, has a great significance in the electric power generation. On the occurrence of any disturbance leads to power imbalance as well as rotor over speeding, consequence is the disconnection of the wind energy conversion system (WECS). This disconnection degrades the voltage restoration and violates the entire stability of the system. The Current grid codes, demand the wind energy system to ensure fault ride through (FRT) ability and contributing network stability. This paper proposed a novel control algorithm to satisfy the grid code requirement. The Proposed controller, forces the WECS to operate away from maximum power point (MPP) during fault condition to reduce the percentage of extracted mechanical power. This reduction in mechanical power assists the stability improvement and suppresses wind generator acceleration. During the normal operating condition, control algorithm forces the gearbox controller to operate at maximum power point to enhance the efficacy of system. This technique is more practical, highly feasible and economically attractive solution compared to other fault ride through technique. The effectiveness of the proposed algorithm is verified by taking different wind speed and gearbox ratio (GB) for squirrel cage based fixed speed induction generator(FSIG). Simulations are carried out using MATLAB/Simulink environment.**

Keywords: Fault ride through, Low voltage ride-through, Variable gearbox, Wind energy conversion system

I. INTRODUCTION

In the increasing demand of electrical energy, the world has claimed the researcher to deal with non-conventional energy and exploits the renewable sources. In this respect, the recent research have been forced towards the enhancement of renewable energy in terms of efficiency and cost-competitiveness. Among the renewable sorcces such as wind, solar and tidle, wind has become the best energy source due to its free availability and environmental friendliness [1-3]. Depending on the control strategy, WECS are basically categorized into two types:

1) Constant speed or fixed speed WECS. This category incorporates squirrel cage induction generator (SCIG)
2) Variable speed WECS and this category includes two sub categories as:
    (i) Full rated converter based WECS (Permanent Magnet synchronous generator)
    (ii) Partially rated converter based WECS (Doubly fed induction generator)

Even though most of the WECS incorporates doubly fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSG), but still a non-negligible portion of wind energy system employs fixed speed induction generators due to their low maintenance cost and simplicity in construction. But the fixed speed wind turbine is greatly affected by voltage sag since the generator is directly coupled to the grid system. On the occurrence of voltage dip, electromagnetic torque (T_{em}) decreases instantly, however mechanical torque (T_m) remains fixed. This circumstance leads to mismatch in torque and consequences is the acceleration in rotor and rotor instability. Hence over-speeding and reactive power requirement should be taken care. Several methods have been discussed in a number of research paper for enhancing the FRT ability of FSIG, which are basically deald with either reduction in rotor over speed or supporting reactive power requirement by introducing superconducting magnetic energy storage (SMES) and FACTS devices [4-6]. Series braking dynamic resistor(SDBR) strategy is adopted in paper [7]. The resistance helps to balance the active power by dissipating the surplus power. SMES is a useful solution for transient stability, voltage and power fluctuations. But this is not a cost effective approach [8]. Paper [9] presents a fault ride through technique which does not dissipates the surplus power during the fault like the braking resistor. Instead dissipating the energy, it stores the input mechanical energy during the grid fault and utilizes at the moment of fault clearance and hence achieves the electromagnetic torque and mechanical torque balance consequently maintains the rotor speed deviation. Therefore this strategy does not require

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additional cost and more practical. The above methods are associated with lowering of electromagnetic power. In case of pitch angle control approach, the input mechanical power is reduced and hence solves accelerating problem of rotor [10]. However due to the physical limitation of the blades and slow operation, pitch controller is not suitable for FRT requirement [8]. This method requires additional controller for preventing over-speeding of wind system. Variabl ratio gearbox(VRG) is supreme appropriate for high reliability of FSWG. The VRG concept is useful for capturing moderate amount of power. By regulating the GB, power capture can be controlled depending on the operating condition. On normal operating condition the GB ratio is set to achieve the maximum power point for enhancing the efficiency of the system however during the fault condition the GB is kept as per requirement to reduce the capture power for reliable purpose. A VRG allows wind turbine to vary the rotor speed and increase efficiency of the aerodynamics system. On the occurrence of fault the extracted mechanical power can be lowered by varying the GB. Variable ratio GB able to enhance the efficacy as rotor speed is varied even if generator is operated at constant speed [11]. It can enhance the power efficiency as much as 35 percent [12]. The paper is organized as follows. Section II represents the modeling of generator. Section III briefly elaborates the concept of variable gear-box ratio. Result and discussion is demonstrated in section IV. Effectiveness is concluded in section V.

II. MODELING OF WIND ENERGY CONVERSION SYSTEM

The basic configuration of a fixed speed WECS is presented in Fig.1 incorporates wind turbine, gearbox, squirrel-cage induction generator and soft starter [13].

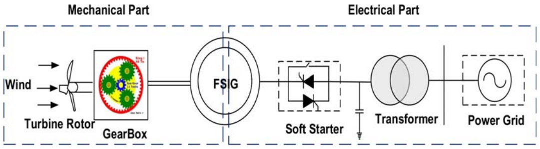

Fig. 1. State space representation of the combined model

The output power of the wind turbine can be represented by Cube law

$$P_m = \frac{1}{2} C_p(\lambda, \beta) \rho A V_\omega^3 \tag{1}$$

where, ρ denotes the density of air in (kg/m^3), r is the radius of rotor blade in (m), C_p is the power coefficient of the wind turbine which is a function of the pitch angle of rotor blades β (in degrees) and tip speed ratio (λ). The expression for λ is given by

$$\lambda = \frac{r \times \omega_{turbine}}{V_w} \tag{2}$$

A standard equation is used for representation of the coefficient of power transfer $C_p(\lambda, \beta)$ based on the modeling turbine features described in [2].

$$C_p(\lambda, \beta) = C_1 \Big(\frac{C_2}{\lambda_i} - C_3 \beta - C_4 \Big) \exp \Big(\frac{-C_5}{\lambda_i} \Big) + C_6 \lambda \tag{3}$$

The values of these parameters are given in Table 1 of the Appendix.

$$\lambda_i = \Big(\frac{1}{\lambda + 0.08\beta} \Big) - \Big(\frac{0.035}{\beta^3 + 1} \Big) \tag{4}$$

By regulating the generator speed (ω_r), optimum tip speed ratio is maintained and ${C_p}^{opt}$ is obtained. In this case, the optimum value of $C_p(\lambda, \beta)$, that is $C_p = 0.48$, is achieved maximum for $\lambda_{opt} = 8.1$ and $\beta = 0^0$. Optimal power is obtained by wind turbine depending on the maximum power coefficient $(C_{P_{max}})$, optimal tip speed ratio (λ_{opt}) and optimum value of pitch angle (β_{opt}).

$$P_{opt} = K_{opt} \times {W_{opt}}^3 \tag{5}$$

$$P_{opt} = \frac{0.5 \rho \pi C_{p_{max}} R^5}{{\lambda_{opt}}^3} \tag{6}$$

Matlab/Simulink model of wind turbine is presented in Fig.2.

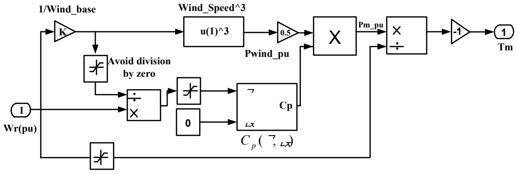

Fig. 2. Matlab / Simulink Model for Wind Turbine

III. VARIABLE RATIO GEAR BOX CONCEPT

The equation for rotation of wind energy system can be expressed as [14]:

$$J \frac{d\omega}{dt} = P_m - P_e \tag{7}$$

where, J represents the moment of inertia, P_m is the mechanical power extracted and P_e is the electrical power generated by the generator system. On the occurrence of fault, terminal voltage at wind generator reduces to zero. Since the electrical power (P_e) is proportional to the square of stator terminal voltage, hence P_e will reduce to zero. The motion equation (7) can be re written as:

$$J \frac{d\omega}{dt} = P_m \tag{8}$$

It is observed that the generator will accelerate till the limit is achieved. The generators continues to absorb reactive power and consequently voltage instability occurs [15]. The variable ratio gear box able to reduce the capturing mechanical power (P_m), hence reduces the acceleration. The output power from the wind turbine (P_m) presented in equation (1), depends on wind speed, and C_p. Hence, mechanical power extracted from wind turbine (P_m) can be regulated by varying C_P. Since C_P is the function of tip speed ratio (λ) and pitch angle (β). However pitch control does not operate within in maximum power point region. So C_P can be varied by regulating λ only. But tip speed ratio (λ) relies on generator speed and wind speed. The variation of C_p with respect to tip speed ratio (λ) is shown in Fig.3. To obtain maximum power point tracking the wind turbine is operated at optimum tip speed ratio, i.e. at maximum power coefficient $(C_p = 0.48)$. The VRG can capable to operate the wind turbine at such a speed to satisfy the optimum tip speed ratio and able to extract the maximum power.

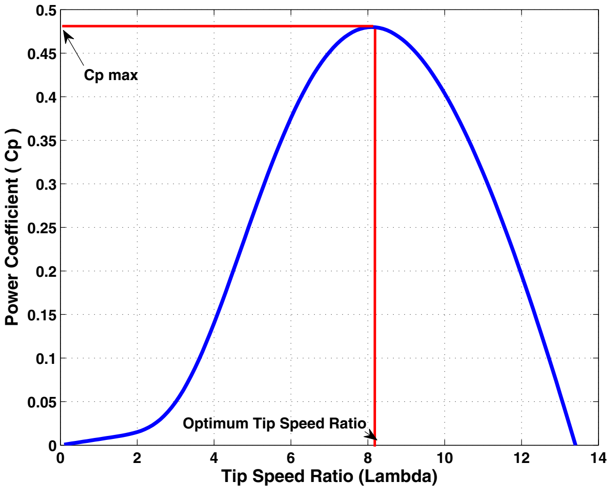

Fig. 3. Power co-efficient (C_p) Vs Tip speed ratio (λ)

The GB can be expressed as:

$$GB = \frac{\omega_{gen}}{\omega_{turbine}} \tag{9}$$

Generator speed (ω_{gen}) is assumed to be constant as the FSWGs operates at constant speed. Hence the expression for $\omega_{turbine}$ can be defined as:

$$\omega_{turbine} = \frac{\omega_{gen}}{GB} = \frac{constant}{GB} \tag{10}$$

From Equation(10), it is observed that by changing GB ratio, wind turbine speed is varied. Hence, the maximum power poit is achived by regulating GB ratio. The Eqn.(2) can be modified by introducing the value of $\omega_{turbine}$ as:

$$\lambda = \frac{r \times \omega_{gen}}{GB \times V_w} \tag{11}$$

During normal operating condition, the GB is regulated to keep λ at its optimum value i.e, λ_{opt}. But the scenario is different during fault condition. During fault, over speeding of the rotor is the predominant issue which persists due to the surplus power. This can be overcome if the mechanical power extracted is reduced. Hence, the controller should force the wind turbine to operate with such GB, so that mechanical power is lowered and surplus power is also reduced. A coordinated control algorithm is presented in Fig.4. The objective is to operate the wind turbine in reduce power mode during the fault condition and extract maximum available power under normal operating condition. During normal operating condition, the main intention is to enhance the efficiency of the system.

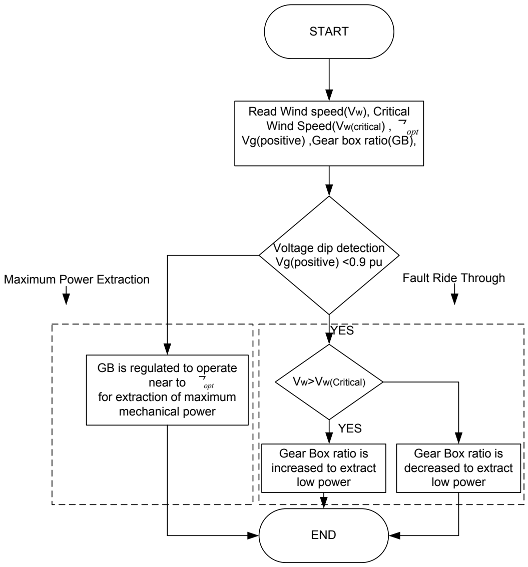

Fig. 4. Coordinated control strategy for FRT and extraction of maximum power

IV. RESULT AND DISCUSSION

Effect of GB variation on λ for turbine is presented in Fig.5 The value of the λ is high for low GB. This conception shift the C_p plot towards the right low GB. During normal

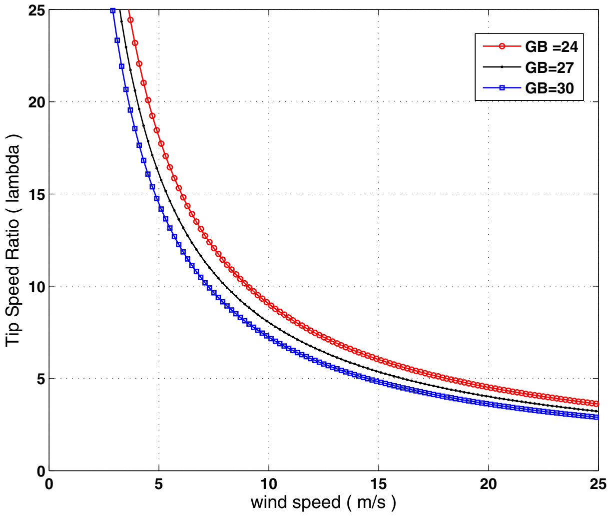

Fig. 5. Variation of λ with respect to GB

operating condition GB is varied in such a way to achieve optimum tip speed ratio. According to equation (11), with increase in GB, the value of λ reduces. In Fig.6 the effect of GB variation on C_p is shown. It is observed that for low wind speed, C_p increases with increase in GB even wind speed remain constant. For wind speed ($V_w = 8$), the C_p at point A is higher than C_p at point B. Point A corresponds to GB=30 and point B corresponds to $GB = 27$. For higher wind speed,C_p decreases with increase in gear ratio (GB). Point D corresponds to GB=24 and point E corresponds to GB=27. C_p at point D is found to be more than the C_p at point E. Critical wind speed ($V_{w,cr}$) is that value of wind speed where relationship between C_p and GB is changed. It is obtained from the intersection point between the maximum and minimum gear ratio curves in Fig.6. The value of critical wind speed relies on turbine characteristics and GB values. The critical wind speed value varies from turbine to turbine. Effect of GB variation on mechanical power extracted (P_m) is presented in Fig.7. From Fig.7 it observed that for low wind speed mechanical power increases with increase in GB. Points G, H, I correspond to GB 30, 27, 24. C_p to point G is higher than power obtained at point H and I. However for higher wind speed ($V_w > V_{w,cri}$) power extracted decreases with increase in GB i.e, J, K, L corresponds to GB 24, 27, 30. Power at point J is more than power at K and L.

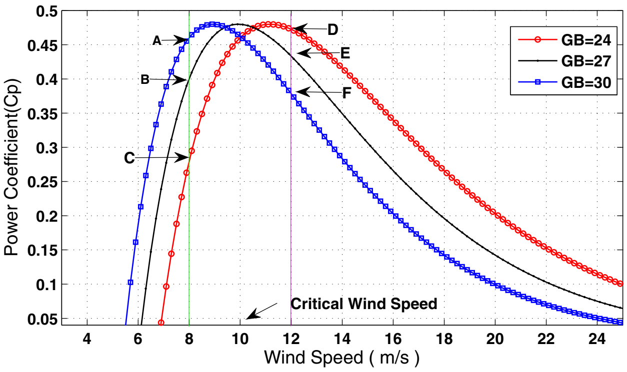

Fig. 6. Effect of GB on power coefficient

In normal operating condition, when there is any variation in wind speed (V_w), tip speed ratio varies as shown in (11). Then the GB should be regulated in such a way to achieve or operate near to maximum power point as shown in Fig.3.

Corresponding GB is calculated by knowing wind speed value. If corresponding λ is less than optimum tip speed ratio (λ_{opt}) then GB is decreased to get higher value of tip speed ratio (Fig.5 shows that increases with decrease in GB). On the other hand if the corresponding λ is more than λ_{opt}, then the extraction power is less shown in Fig.3 and GB is forced to increase to for obtaining lower λ. During the fault condition critical wind speed (V_w, cr) is the deciding factor for GB setting. It is also observed from Fig.6 and Fig.7, that if the (V_w) is less than the V_w, cr then mechanical power extraction decreases with decrease in GB and if the (V_w) is more than V_w, cr, mechanical power extraction (P_m) decreases with increase in GB. Hence, GB should be adjusted to decrease the mechanical power extraction during fault period.

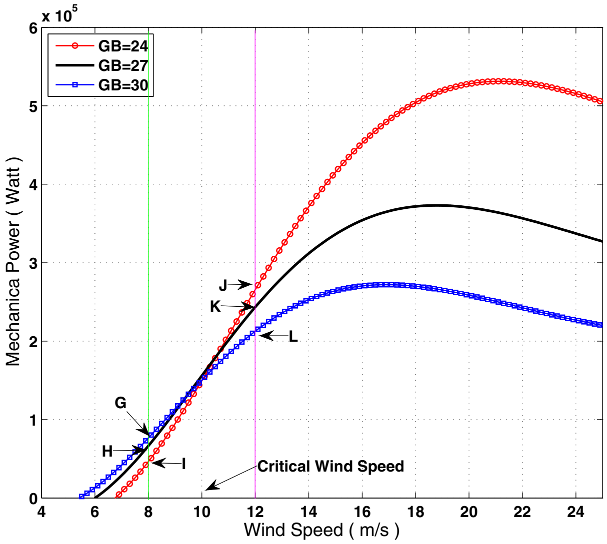

Fig. 7. Effect of GB on mechanical power extraction from wind turbine

V. CONCLUSION

In this paper a variable ratio GB concept is discussed for FRT operation along with maximum power extraction. A coordinated control algorithm is presented which aimed to achieve ride through the system during abnormal condition for satisfying the grid code requirement and enhance efficiency during the normal condition. This method does not require additional cost as FSWGs incorporates gearbox and for efficiency improvement variable ratio gearbox concept is adopted. Gearbox effectively reduces the mechanical power captured and hence successfully decrease the rotor acceleration and rotor instability. This method only requires the variable ratio gearbox controller to be modified during fault condition. The technique is cheap, practically suitable and reliable too.

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APPENDIX

Tables I and II are the parameters of the FSIG used in the simulative tests of this paper.

TABLE I

PARAMETER OF WIND TURBINE

$Wind\ turbine\ type$	$Fixed\ speed$
$Rotor\ diameter$	26 m
$Gearbox\ ratio$	$24, 27, 30$
C_1	0.5176
C_2	116
C_3	0.4
C_4	5
C_5	21
C_6	0.0068

TABLE II

PARAMETER OF SCIG

$Number\ of\ pole\ pairs$	3
$Rated\ voltage\ (line\ to\ line)$	0.48 kV
$Stator\ resistance$	0.00185 ohm
$Rotor\ resistance$	0.017 ohm
$Rotor\ leakage\ inductance$	1.3210^{-5} H
$Magnetic\ inductance$	2.06^{-3} H
$Generator\ inertia$	59.26 kgm^2 H

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